# THERMAL NEUTRONS IN EAS: A NEW DIMENSION IN EAS STUDY[1]

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**Abstract**

A new method to study Extensive Air Shower (EAS) hadronic component is proposed. It is shown that addition of specific detectors for thermal neutron detection to a standard array for EAS study can significantly improve its performance. Results of CORSIKA based Monte Carlo simulations as well as preliminary experimental data are presented. A proposal of novel type of EAS array is given.

## 1 Introduction

The study of cosmic ray neutron component started in 30-s of last century. A summary of the early experimental data and their interpretation can be found in [1]. Later, in 40-s, in parallel with understanding of the EAS hadronic structure, measurements of neutron component in EAS have began [2, 3, 4]. All the data obtained in these early works were correctly understood and interpreted. Later, when the neutron monitors [5] were constructed and spread widely, people tried to use them in conjunction with EAS arrays to study hadronic component of secondary cosmic rays (see for example [6, 7, 8, 9]). Many "anomalies" were observed in these experiments: in hadron spectrum [7], in lateral distribution [8], etc. Explanations of these "anomalies" can be found in an *a priori* assumption that they recorded a single hadron. But, with primary energy rising, there will be a moment when the number of hadrons entering the monitor becomes bigger then 1. This is a new class of events, which we called as *hadron group* [10]. Starting from this moment, all secondary processes including evaporation neutron production, depend mostly on the hadrons number reached the detector instead of their energy rising very slowly. This results in sharp changes in many observables: locally produced neutrons number distribution becomes flatter, their lateral distribution becomes difficult for interpretation while it remains constant for each center of generation (for each interacting hadron).

The idea to use neutrons moving with sub-luminal velocity at a long distances from EAS core for the estimation of hadronic component energy, has been proposed by J. Linsley [11].

The idea to use thermal neutrons as a key to select muon hadronic interactions underground has been proposed and realized by G.T.Zatsepin and O.G.Ryazhskaya [12, 13]

## 2 A prototype of the MultiCom array

A novel type of an array for EAS study (MultiCom) prosed by us in 2001 [14, 15], has been realized in 2005 near the existing Baksan Carpet-2 EAS array as a prototype, consisting of one working module of $5 \times 5 m^2$. 4 thick liquid scintillator detectors ($70 \times 70 \times 60 cm^3$) in the corners were used for triggering with a threshold of 106 MeV in each detector. The trigger counting rate is equal to 3.3 $min^{-1}$. Additional requirement for event to be stored (software trigger) is energy deposit in the central ZnS detector equivalent to 1/2 of the most probable neutron pulse height (or ∼8 relativistic particles). Corresponding energy threshold for such trigger conditions

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was calculated to be $\sim 7$ TeV for proton originated EAS, $\sim 30$ TeV for He EAS and $\sim$300 TeV for Fe EAS. In the center of module there is situated unshielded thermal neutron detector of $0.7m^2$ at 2.5 m above ground level (fig. 1). We used a thin layer of a mixture of old inorganic scintillator ZnS(Ag) with LiF enriched with $^6Li$ up to 90%. Thermal neutrons are recording due

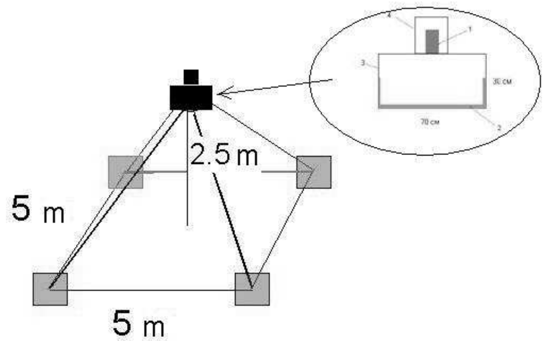


Figure 1: MultiCom prototype set-up.

to $^6Li(n,\alpha)^3H + 4.78$ MeV reaction. ZnS scintillator is the best scintillator for heavy particle detection and produces $\sim 160,000$ light photons per one captured neutron. That means one could make a large detector viewed by a single PMT and have enough light. In our case we have $\sim$50 photo-electrons from PMT photo-cathode.

The efficiency of thermal neutron detection was found to be 20%. Pulse duration (the fastest component) is equal to $\sim 40$ ns. Due to very thin scintillator layer ( 30 $mg/cm^2$), it is almost insensitive to single charged particles and gamma-ray, but it can be successfully used for EAS particle density measurements as it will be shown below.

4-channel digital oscilloscope TDS224 connected to a PC via GPIB interface is used for data acquisition. Integrated analog pulses from the PMT anode are put to the oscilloscope inputs with different gain. Digitizing step is equal to 4 $\mu s$ while full time scale is equal to 10 ms. Full wave form information is collected in a case of the event.

## 3 Experimental results

The results of this experiment can be found elsewhere [16, 17]. Here only additional information will be shown with the aim to illustrate the method performances. First of all, we have measured the thermal neutron yield per event, which was found to be equal to $< n > \approx 0.15$ for our event threshold. The time structure of delayed pulses distribution can be fitted in an interval of 10 ms by a double-exponential function of a type: $F(t) = C(exp(-t/\tau_1) + exp(-t/\tau_2))$ with parameters C, $\tau_1$ and $\tau_2$ depending on the charged particle density measured by the ZnS detector and thus depending on the EAS size. The higher size, the more steep is the time distribution. It is interesting that $\tau_1 \approx 2\tau_2 \approx 9.0$ ms for all events and $\approx 5.0$ ms for events with central density $\rho > 800m^{-2}$. This experimental fact has to be understood and explained. Unexpectedly flat neutron time distributions could be explained as follows. As it was mentioned above, the mean efficiency for neutron detection in our detector is close to 20%. But, this value was obtained taking into account spacings between the scintillator grains, while the efficiency to detect thermal neutron by the scintillator grain ($0.5 \div 0.8mm$) was calculated to be equal to 74%. Measured flux

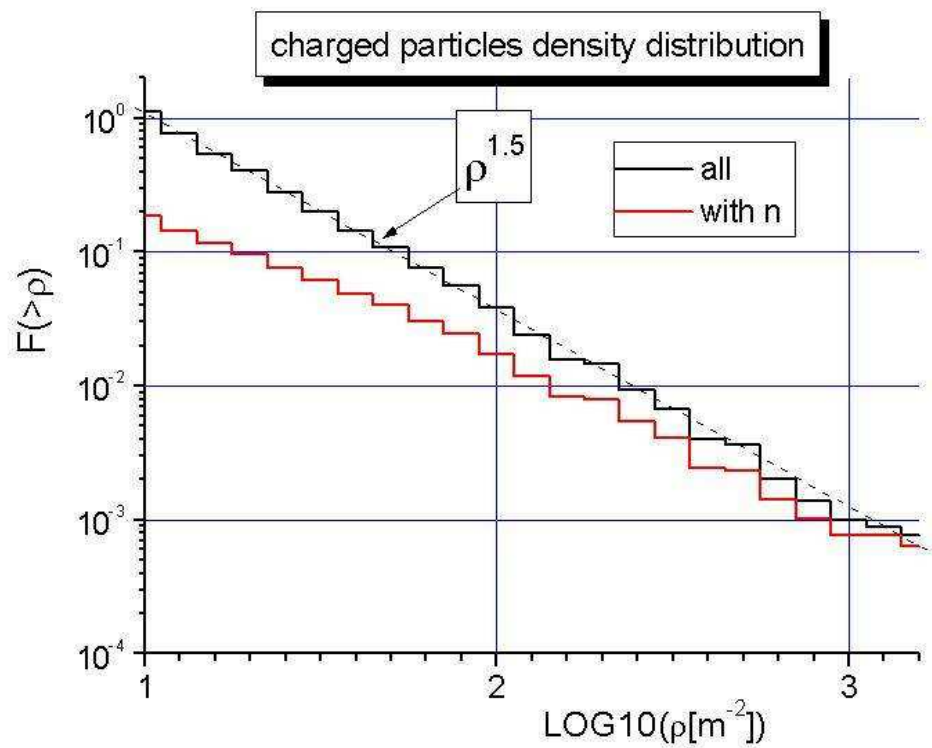


Figure 2: Charged particle density distributions measured by the ZnS detector.

is $F = n \times v \times \varepsilon$, where n is neutron concentration, v is neutron velocity and $\varepsilon = 1 - exp(-\lambda t)$ is the detection efficiency. Here $1/\lambda$ is neutron mean free path and t is mean grain thickness. It is well known that $\lambda \sim 1/v$ for thermal and slow neutrons. Therefore, $F \approx n$ in a case of fast neutrons and $F \approx n \times v$ for slow neutrons. That means that the scintillator is thick enough for thermal neutrons, while it is thin for fast neutrons. This results in very flat time distributions (concentration does not changes very quickly) after the EAS passage and their independence on the media temperature. In contrast to this case, in a stationary regime when neutron velocity are in equilibrium with medium (background measurements) $F \approx n \times v$ and this value depends on the media temperature [18] as $F \sim \sqrt{T}$ due to Maxwell velocity distribution. A possibility to measure charged particles number passed through the ZnS detector is demonstrated in the fig. 2, where energy deposit spectra of the EAS particles are presented as measured by the ZnS detector . As one can see, the measured particle density spectrum for all evens follows well known power law function with integral index equal to $\sim -1.5$, while that for events with recorded neutrons changes the slope. At high enough density of about $10^3$ $m^{-2}$ almost all events are with neutrons and the spectra equalize. These figures confirm that our ZnS detector works properly not only for neutron detection but for charged particles as well.

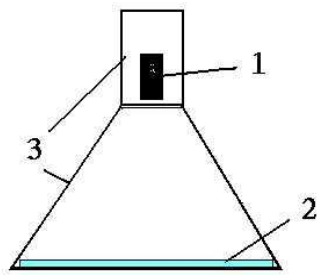


Figure 3: Possible design of the $1 - m^2$ ZnS detector. 1 - 6" PMT ; 2 $-ZnS+^6Li$ mixture; 3 - housing.

# 4 The e-n-array proposal

The first obtained experimental results as well as results of Monte Carlo simulations, made on a base of CORSIKA codes (v. 6012, HDPM and Gheisha models), makes me sure to propose a novel type of EAS array which could consist only of the large area ZnS detectors measuring both the main EAS components: hadronic and electromagnetic. The array could look like a simple grid of say 121 detectors like those shown in fig.3, with spacing $5 \div 10$ m covering an area of $100 \times 100$ $m^2$. It could be very informative in spite of its simplicity and compactness. Detection of thermal neutron flux accompanying the EAS passage through the surrounding matter gives absolutely new information, which was never used before. First of all, the number of detected neutrons is proportional (in the first approximation) to the number of hadrons reached the observational level in a radius of $\sim$ 300$\div$500 m around the detector location, including an air layer of the same thickness. Such a large distance evaporation neutrons can cover during their movement in air before moderation. Detailed study of hadronic component with a large area detector ($10^4$ $m^2$ in proposed array, which can be extended without any problem) is very interesting problem because hadrons form the EAS skeleton and only they can preserve the adequate information about primary particle. Starting from a low threshold on primary energy of $\sim 10 \div 30$ TeV and covering the "knee" region with a wide enough range, this array could make a significant improvement of experimental situation and probably would solve the "knee" problem. Another interesting advantage of the array is its possibility to locate the EAS axis more precisely due to steep lateral distribution of hadronic and neutron components (see fig.4) in comparison with electron one usually used for this purpose. That means primary energy can be recalculated with higher accuracy. A usage of $n/e$ -ratio instead of $\mu/e$-ratio for primary mass composition measurements would give better results because of first, a number of thermal neutrons is much higher than a number of muons and second, electron and hadron components are in equilibrium on an observational level, while muonic component is not, due to its integral properties [16]. And finally, the time structure of the *neutron vapor* is absolutely new dimension in EAS study, which could give us unexpected result.

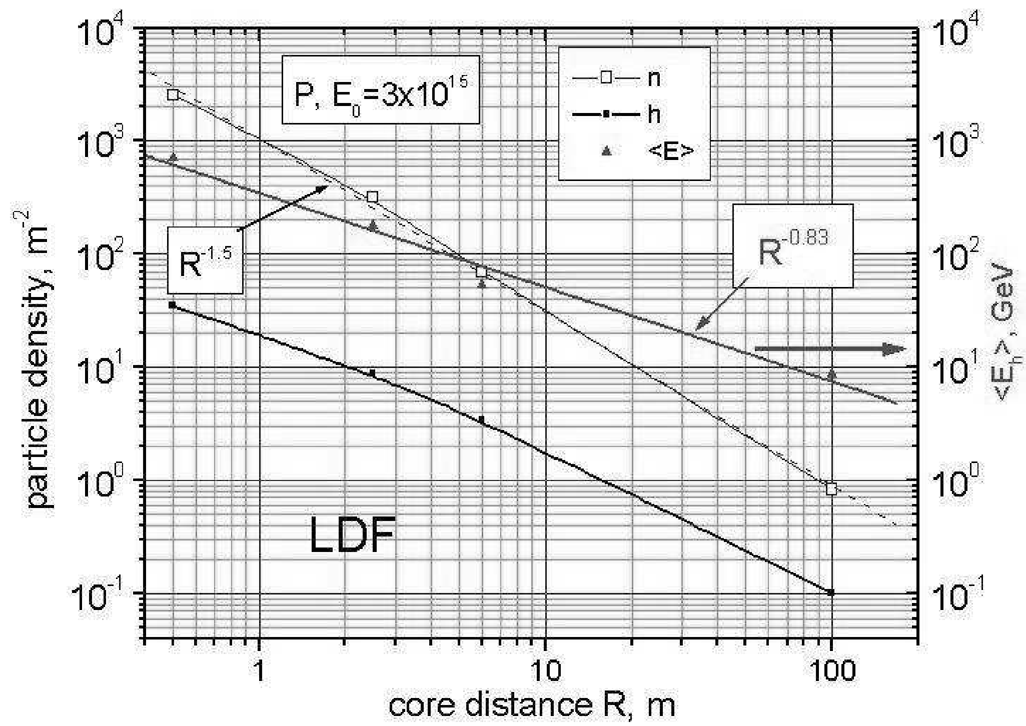


Figure 4: Results of Monte Carlo simulations for hadron and neutron lateral distribution and mean hadron energy as a function of core distance for primary proton of 3 PeV.

## 5 Summary

The method to study EAS with thermal neutron scintillator detectors proposed in 2001 was checked with a one-module prototype. Promising data obtained with a pioneer experiment let me to conclude that *the neutron vapor* associated with EAS passage does exist and can provide experimenters with an additional very useful information. On this basis a novel type of a very simple array is proposed which could use this additional dimension in EAS study. A scintillator detector for neutron detection developed by us showed very good performance and made it possible to measure thermal neutron flux with very low background. Moreover, it showed rather good performance in charged particle density measurements thus lead us to a conclusion that EAS array could consist only of these detectors measuring both main EAS components hadronic and electronic. Rather fast pulse width of $\sim$ 40 ns allows one to use these detectors even for the EAS arrival direction determination if one need not very good angular resolution. Finally, the detector showed an excellent performance in thermal neutron background flux measurements. First very interesting results of this study can be found in [18].

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